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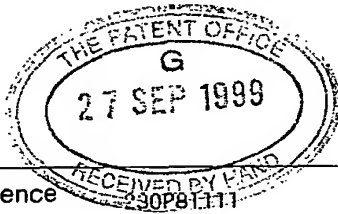
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Your reference   230P81111

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Request for grant of a Patent

Form 1/77   Patents Act 1977

❶ **Title of invention**

1   Please give the title   A Radiation Source.
     of the invention

❷ **Applicant's details**

❑   **First or only applicant**

2a   If you are applying as a corporate body please give:

     Corporate name
                          Toshiba Research Europe Limited

     Country *(and State
     of incorporation, if   United Kingdom
     appropriate)*

2b   If you are applying as an individual or one of a partnership please give in full:

     Surname

     Forenames

2c   **In all cases**, please give the following details:

     Address
                          Cambridge Research Laboratory,
                          260 Cambridge Science Park, Milton Road,
                          Cambridge, CB4 0WE, United Kingdom
                          United Kingdom

     UK postcode
     (if applicable)

     Country

     ADP number
     (if known)   751 413 6002

2d, 2e and 2f: If there are further applicants please provide details on a separate sheet of paper.	☐ **Second applicant** *(if any)* If you are applying as a corporate body please give: Corporate name Country *(and State of incorporation, if appropriate)*
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3a Have you appointed an agent to deal with your application?

Yes [X]　　No [ ] ➡ *go to 3b*

⬇

please give details below

Agent's name　　Marks & Clerk

Agent's address　57-60 Lincoln's Inn Fields
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5 Claiming an earlier application date

5   Are you claiming that this application be treated as having been filed on the
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Yes ☐   No ☒ → **go to 6**

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15(4) (Divisional) ☐   8(3) ☐   12(6) ☐   37(4) ☐

6 Declaration of priority

*If you are declaring priority from a
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❼ Inventorship

Are you (the applicant or applicants) the inventor or the joint inventors?

Please mark correct box

Yes ☐   No ☒ ➡ *A Statement of Inventorship on Patents Form 7/77 will need to be filed (see Rule 15).*

❽ Checklist

8a   Please fill in the number of sheets for each of the following types of document contained in this application.

Continuation sheets for this Patents Form 1/77 [——]

Claim(s) [3]   Description [19]

Abstract [1]   Drawing(s) [16+16]
(INFORMAL).

8b   Which of the following documents also accompanies the application?

Priority documents *(please state how many)* [——]

Translation(s) of Priority documents *(please state how many)* [——]

Patents Form 7/77 – Statement of Inventorship and Right to Grant [1]
(please state how many)

Patents Form 9/77 – Preliminary Examination/Search [1]

Patents Form 10/77 – Request for Substantive Examination [1]

❾ Request

I/We request the grant of a patent on the basis of this application.

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M&C Folio: 230P81111   Document #: 425455

A Radiation Source

The present invention relates to a radiation source for emitting radiation with frequencies ranging from the high Gigahertz range (GHz) up to an including the Terahertz range (THz). All such radiation is colloquially know as THz radiation, especially that in the range from 0.1 THz to 100 THz. More specifically, the present invention relates to a magnetically enhanced radiation source for such radiation.

Recently, there has been much interest in using THz radiation to look at a wide variety of samples using a range of methods. THz radiation has been used for both imaging samples and obtaining spectra. Recently, work by Arnone et al, SPIE, European Conference Munich, June 1999, illustrates the use of THz radiation to image types of human and non human tissue.

THz radiation is of particular use because it penetrates most dry, non metallic and non polar objects like plastics, paper, cardboard and non polar organic substances. Therefore, THz radiation can be used instead of x-rays to look inside boxes, cases etc. THz has lower energy, non-ionising photons than X-rays, hence, the health risks of using THz radiation are expected to be vastly reduced compared to those using conventional X-rays.

To improve the usefulness of such THz radiation, there is a need to produce a THz source which can produce a relatively high energy beam of THz. To date, there are no compact solid state sources of THz radiation. However, recent advances in ultra fast pulsed lasers operating in the near infrared and visible have allowed coherent, broadband THz pulses to be produced from semiconductors. There are three widely-used methods for generating coherent THz from semiconductors irradiated by such ultrafast pulses : optical rectification, the surface field photocurrent effect, and lateral

photocurrent effect using antennas. THz radiation is produced by irradiating a semiconductor material which possesses suitable properties with an input beam of optical or infra-red radiation which can be produced by a standard laser such as a Ti:Sapphire Laser. It would seem logical that to produce a strong THz source, all is required is a stronger input beam. However, this is not the case as the power of the emitted THz beam saturates as the power of the input beam is increased. Also, higher input beam powers may damage the crystal being irradiated.

It has been previously suggested that the THz output of such a semiconductor material can be controlled by subjecting the material to a magnetic field. Zhang et al. Appl. Phys. Lett 62 2003 (1993) showed that the direction and polarisation of a THz beam produced from a non-linear semiconductor crystal (in this case GaAs) could be controlled by subjecting the non-linear material to a magnetic field. The magnetic field here was oriented perpendicular to both the input beam and the THz beam. The THz beam was produced by transmission of the input beam through the non-linear material.

Some et al. Phys. Rev. B 53, R13 295 (1996) also used transmission geometry to investigate how THz emission using transmission geometry was affected by an applied magnetic field. Here, the field was applied both perpendicular to the input beam (and hence perpendicular to the emitted beam) and also at an angle of 25° from the input beam.

Sarukura et al. Appl. Phys. Lett. 84, 654 (1998) have recently shown enhanced THz emission using reflection geometry. Here, the non-linear material was positioned at 45° to the input beam, such that the emitted (or more correctly, the reflected) beam and input beam are arranged at right angles. In this arrangement, the magnetic field was arranged parallel to the input beam, but perpendicular to the emitted beam. Using a magnetic field with a strength of 1.7T, Sarukura et al. achieved a 650μW THz beam with a 1.5 W excitation power.

The present invention addresses the above problem of providing an enhanced THz source which has achieved better results than the previously discussed methods. In a first aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to irradiation with an input beam with a frequency different to that of the emitted radiation, the source being subjected to a magnetic field which has a component parallel to that of the emitted beam of radiation, the emitted beam of radiation being produced by reflecting the input beam off a surface of the frequency conversion member.

Preferably, the emitted radiation has a frequency in range of 1THz to 84THz. More preferably, from 1 THz to 20 THz.

Reflection geometry is chosen as there are losses in the radiation power as the THz beam transverses the frequency conversion member in transmission geometry.

The radiation source of the present invention is capable of producing a more efficient THz beam. The source of Sarukura et al. is capable of a conversion efficiency of 4.3×10^{-5}. However, the present invention is capable of a conversion efficiency in excess of this figure. For example, the present invention has obtained conversion efficiencies of 4.3×10^{-3}.

Preferably, the magnetic field is arranged at an angle of 20° or less to the emitted or reflected beam. More preferably, the magnetic field is arranged completely parallel to the emitted or reflected beam.

A number of different frequency conversion member could be used for example $LiIO_3$, $NH_4H_2PO_4$, ADP, KH_2, A_5O_4, Quartz, $AlPO_4$, ZnO, CdS, GaP, GaAs, $BaTiO_3$, $LiTaO_3$, $LiNbO_3$, Te, Se, ZnTe, ZnSe, $Ba_2NaNb_5O_{15}$, AgAsS3, proustite, Cd, Se, CdSe, $CdGeAs_2$, $AgGaSe_2$, $AgSbS_3$, ZnS, BBO, KTP, DAST (4-N-methylstilbazolium),

L4NbO3. The frequency conversion member will preferably be one of InAs, InSb or GaAs.

The magnetic field may be generated by an electro-magnet or a permanent magnet.

Preferably the frequency conversion member is cooled.

It has previously been shown that a large Faraday effect can be seen in semiconductors which have been doped using magnetic ions such as Mn. Such 'magnetically doped' structures can also exhibit enhanced THz emission in a magnetic field. Therefore, in a second aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the frequency conversion member being doped with a magnetic material.

More preferably, the magnetic dopant is Mn.

It has also been found that THz emission can be enhanced by applying both a magnetic and an electric field to an emitter crystal. Therefore, in a third aspect, the present invention provides a radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the source further comprising means for applying an electric field at the surface of the frequency conversion member which is irradiated by the input beam.

Preferably , the magnetic dopant comprises Mn. Also, the input beam is preferably circularly polarised.

In the radiation sources of the second and third aspect of the present invention, the magnetic field preferably has a component parallel to that of the emitted beam. More preferably, the magnetic field is at an angle of at most 20° to the emitted beam.

More preferably, the emitted beam is produced by reflection of the input beam off a surface of the frequency conversion member.

The means for applying the electric field can be provided by two Ohmic contacts made to the frequency conversion member and means for applying a bias to accelerate the photocarriers between these two contacts. The Ohmic contacts may be shaped so that they taper towards one another. In other words, they form a "bow-tie" shape.

The means may also be provided by a front gate which overlies the surface of the frequency conversion member which is irradiated by the input beam.

Experiments using sources according to the above mentioned aspects of the present invention have shown that the conversion efficiency does not saturate with magnetic field. Therefore, preferably, the frequency conversion member is subjected to a magnetic field of at least 2T.

Typically, the wavelength of the input or pump beam will be such that the photon pump energy is larger than the band gap of the frequency conversion member. Preferably, source will be configured such that the input beam is at the Brewster angle of the frequency conversion member, i.e. at the Brewster angle to the surface normal. The Brewster angle will be about 70° to the surface normal. Therefore, typically, the input beam will be preferably arranged between 45° and 85°, more preferably between 60° and 80°.

It should be noted that a radiation source may be provided which comprises both a magnetically doped frequency conversion member and means for applying an electric

field to the frequency conversion member. This source may also be configured with the reflection geometry of the first aspect of the present invention.

In a fourth aspect, the present invention provides a source comprising a frequency conversion member configured to reflect a beam of reflected radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the reflected beam and a magnet for subjecting the conversion member to a magnetic field which has a component parallel to that of the reflected beam.

The present invention will now be described with reference to the following preferable, non-limiting embodiments, in which:

Figure 1 is a schematic of a source in accordance with an embodiment of the present invention;

Figure 2 is a schematic of the experimental arrangement to measure a source according to an embodiment of the present invention;

Figures 3a and 3b are plots of the transverse magnetic and transverse electric polarisation direction of a THz electric field emitted by a source according to an embodiment of the present invention;

Figure 4 shows a plot of the transverse magnetic polarisation component of a THz emission spectra form a source according to an embodiment of the present invention;

Figures 5a and 5b show plots of the power calculated from the transverse magnetic and the transverse electric polarisations respectively, figure 5c plots the total power;

Figure 6 is a plot of THz power from an InAs source according to an embodiment of the present invention;

Figure 7 shows a plot of THz conversion efficiency and THz pulse energy against the energy of the visible pulse;

Figure 8 is a plot comparing the efficiency of THz generation according to an embodiment of the present invention as compared with the known prior art;

Figure 9 shows a compact THz emitter in accordance with an embodiment of the present invention;

Figure 10 shows a compact THz emitter in accordance with a further embodiment of the present invention;

Figure 11 shows a compact emitter in accordance with another embodiment of the present invention;

Figure 12 shows a THz emitter in accordance with another embodiment of the present invention;

Figure 13 shows a variation on the emitter of Figure 12;

Figure 14 shows a magnetically doped THz emitter in accordance with an embodiment of the present invention;

Figure 15 shows an experimental arrangement for detecting THz radiation from the source of Figure 14;

Figure 16 shows an embodiment of the present invention which uses an electric field as well as a magnetic field to enhance THz production; and

Figure 17 shows a further embodiment of the present invention where a front gate overlies a surface of the THz emitter.

Figure 1 shows a THz emitter according to an embodiment of the present invention. The THz emitter has a frequency conversion member 1 which is either InAs, InSb, or GaAs.

It should be noted that other types of frequency conversion member are possible either crystalline or non-crystalline. For example, $LiIO_3$, $NH_4H_2PO_4$, ADP, KH_2, A_5O_4, Quartz, $AlPO_4$, ZnO, CdS, GaP, GaAs, $BaTiO_3$, $LiTaO_3$, $LiNbO_3$, Te, Se, ZnTe, ZnSe, $Ba_2NaNb_5O_{15}$, AgAsS3, proustite, Cd, Se, CdSe, $CdGeAs_2$, $AgGaSe_2$, $AgSbS_3$, ZnS, BBO, KTP, DAST (4-N-methylstilbazolium), L4NbO3.

A pump beam 3 is directed towards member 1 at an angle θi to the surface normal of member 1. The pump beam is reflected from the surface 5 of emitter 1 as a THz beam at an angle θr to the surface 5 normal. The emitter is subject to a magnetic field along the direction of the emitted THz beam 7. As the magnetic field direction 9 is parallel to the direction of the THz beam 7, both the transverse electric PTHzTE and the transverse magnetic PTHzTM polarisation components of the THz beam are subject to a magnetic field.

The pump beam will typically have wavelengths in the range 2μm to 350nm. The pump wavelength will be such that the pump photon energy is larger than the band gap energy of the frequency conversion member 1. The pump beam will be a pulsed beam with a plurality of frequencies contained within each pulse. The semiconductor frequency conversion member 1 can emit a THz beam that is a difference of two of the frequencies in the pump beam.

Figure 2 shows an experimental arrangement which is used to generate THz in accordance with an embodiment of the present invention. A mode-locked Ti:Sapphire Laser 21 produces a beam 23 of 90 fs pulses at a wavelength of 790nm and a repetition

rate of 82MHz. Beam 23 yields 0.8W average power and has pulse energies in the nJ range. Beam 23 is split by beamsplitter 25 into a pump beam 27 and a probe beam 29. Eventually, it will be required to bring the probe beam and the pump beam back into synchronisation with one another or change the temporal shift between the pump beam and the probe beam. Therefore, the pump beam 27 is reflected off mirror 31. Thus, the path length of pump beam 27 can be varied. Mirror 31 reflects pump beam 27 through half wave plate 33 and into polariser 35. The polariser 35 transmits the beam onto mirror 37 which then reflects the beam through lens 39 and cryostat windows (e.g. Spectrosil B) 41 and 43 onto crystal 45. After the beam has passed through chopper 38, the beam is transmitted through lens 39. Crystal 45 is a frequency conversion member and is situated in a magnetic field. Emitter crystal 45 is also angled at 45 to the incident pump beam 27. Chopper 38 functions to chop the beam at a certain frequency. This can improve detection as the beam can be detected at the chopper 38 frequency using a lock-in amplifier. For this type of system, the chopper 38 will preferably be an acousto-optic modulator. Angles of Brewster's angle for the crystal source in question are preferable. For InAs, InSb and GaAs, the Brewster angle is about 70°. Thus, a reflected THz beam 47 is reflected from crystal 45 at an angle of 90 to pump beam 27. The magnetic field generated by a split coil superconducting magnet 49 is parallel to the direction of the emitted THz beam 47. The emitted THz beam 47 is then passed through cryostat window 53 and THz polariser 55.

Figure 2 shows two methods for detecting the THz. The first of these is bolometer 57. This a He-cooled bolometer which is placed immediately after the cryostat to allow efficient collection of the emitted THz. Bolometer 57 measures both coherent and incoherent contributions to the THz power. In both detection mechanisms, polariser 55 allowed selection of either the transverse electric or transverse magnetic THz polarisation with a 10% transmission loss. Losses by other elements in the THz beam path were determined using an infra red transform spectrometer and accounted for 50% loss at a frequencies of 1THz. The visible pump beam was also attenuated by 19% due to cryostat windows.

Either instead of or in addition to the bolometer, an electro-optic sampling detection mechanism 59 is also present in the apparatus of Figure 2.

The electric-optic sampling system 59 relies on the ac pockels effect. The THz beam 47 is combined with pump beam 29 using mirror 61. Before passing through the back of mirror 61, probe beam 29 is passed through a polariser 63. The combined THz beam 47 and probe beam 29 are then directed onto a 1mm thick (110) ZnTe crystal. Due to the ac pockels effect, the presence of THz beam 47 causes a rotation in the polarisation of pump beam 29. Therefore, the presence of THz can be detected. When the combined beam 63 has passed through detection crystal 65, it is then transmitted through quarter wave plate 65 to a Wollaston Prism 67 (or other polarisation splitting device) onto balanced photodiode arrangement 69.

If the polarisation of probe beam 29 has not been rotated, the balanced photodiode assembly will read 0. However, if the polarisation of the probe beam 29 has been rotated, there will be a difference in the intensity of the beams split by the Wollaston Prism which are detected by two photodiodes within the balance photodiode assembly 69. The difference in the output of the photodiodes will cause the magnitude of the output of the balance photodiode assembly to be greater than 0. The amount by which the polarisation of the probe beam 29 is rotated by the THz beam 47 is dependent on the intensity of the THz beam 47. Therefore, the output of the balance photodiode assembly 69 directly measures the electric field of the THz beam.

The evolution of the field with time is measured by varying the delay (via mirror 31) between the visible pump 27 and probe beams 29. The power spectrum associated with the THz radiation may be obtained by Fourier transforming the time-domain data. The bandwidth of the THz pulse measured using the electro-optic sampling detector 59 of Figure 2 extends from 0.5 THz to 2.7 THz. This bandwidth is in part constrained by the thickness of the detector crystal and prevents highly accurate measurement of enhancement at frequencies outside this range.

Figure 3a shows the variation in the intensity of the THz signal as the time delay between the probe beam and the pulse beam is varied using mirror 31 for magnetic fields from 0T-8T. Figure 3a shows the results for transverse magnetic polarisation and Figure 3b shows the results of transverse electric polarisation.

Figure 4 shows the THz power measured using the experimental set up of Figure 2 as a function of frequency obtained by Fourier transforming time-domain spectrum of the type shown in Figures 3a and 3b. An enhancement occurs across the most accessible THz bandwidth, accompanied by a relatively large increase of the power at frequencies above 2.7 THz. The behaviour was also observed for the transverse electric polarisation and was reproduced in spite of the reduced accuracy of detection in this range.

The amount of coherent power can be determined from the area under the frequency of the main power spectrum between 0.5 and 2.7 THz. Calculating this power for both polarisation components, ie. transverse magnetic and transverse electric allows a direct comparison with magnetic field dependence of the bolometer measurements which are shown in Figure 5.

The dependence of the THz power on magnetic field is similar with the electro-optic sampling detector 59 and the bolometer 57 suggesting that the majority of field enhanced emission is coherent. There is a decrease in the intensity of the transverse mechanic polarisation component B>6T which is not present in the bolometer measurement. This suggests that there may be a peak in the enhancement of a coherently generated THz for this polarisation. Such a peak is not observed in the transverse electric polarisation. These results suggest a further increase in magnetic field B were yield in a larger enhancement of the coherently generated THz power.

Figure 6 shows the dependence of the bolometer power on magnetic field for both of the individual polarisation components (i.e. transverse electric and transverse magnetic) as well as the total value. It can be seen that if the magnetic field is increased, both polarisation components are also increased. The total power is 486μW at 8T after

accounting for losses in both the cryostat and the polariser. Path lengths between the cryostats outer window and the bolometer were kept less than 5cm to minimise atmospheric absorption of the THz. Therefore, with an average incident pump power at the sample of 113mW, the average power visible to average THz power·conversion efficiency is 0.43%.

These results clearly suggest that going to even higher magnetic fields will result in even higher THz efficiency.

Figure 7 shows results taken at 8T and 180K for (100)InAs as a generator crystal. Sample geometry is the same as that described with reference to Figures 1 and 2.

The x-axis shows the variation in the visible pulse energy of the pump beam. The left-hand y-axis shows the visible THz conversion efficiency and the right-hand y-axis shows the measured THz pulse energy. The open symbols shows the energy for an unamplified, conventional oscillator source, and the closed symbols show those for an amplifier system. The lines through the closed symbols and the open symbols relate to a double exponential fit to the results. This graph suggests that increasing the visible pulse energy does not necessarily provide an increase THz signal. Therefore, other methods of increasing the THz signal are of commercial significance.

Figures 8a and 8b compare results taken in accordance with an embodiment of the present invention. With those of the known prior art. Specifically, the data points A to J are as follows:

A.   1mm (110) ZnTe at room temperature, with no magnetic field. Pumped with 100mW from an oscillator.

B.   (100) InAs at 173K and B=8T, applied parallel to the direction of the THz beam. Pumped 130mW average power from an oscillator in accordance with an embodiment of the present invention.

C.   (100) InAs at 173K and B=8T, applied parallel to the direction of the THz beam.

Pumped 83mW average power (0.33μJ pulse energy) from an amplifier in accordance with an embodiment of the present invention.

D.   (100) InAs at room temperature and B=1.7T, applied perpendicular to the direction of the THz beam. Pumped with 1.5W from an oscillator. (Sakura et al, J. App. Phys. **84** 654).

E.   Large aperture photoconductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 882mW (4.4μJ) from an amplifier. (Mouret et al Microwave Opt. Tech. Lett. **17** 23).

F.   Large aperture photoconductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 500mW (500μJ) from an amplifier. (Budiarto et al IEEE J. Quant. Elec. **32** 1839).

G.   Large aperture photo conductive antenna on SI GaAs at room temperature, no magnetic field. Pumped with 2.8mW (282μJ) from an amplifier. (You et al Opt. Lett. **18** 290).

Figure 9 shows a compact emitter in accordance with an embodiment to the present invention. The emitter comprises an electro magnet or a permanent magnet 71 which has a hole 73 formed therethrough. Hole 73 completely penetrates the magnet 71 and defines a space for the THz emitter space. The space is boarded on four sides by magnet 71 and at the upper 78 and lower 77 surfaces by non-magnetic material. The visible pump beam 75 enters the lower surface 77 of the emitter space 73. The pump beam 75 enters the emitter through pump window 79. The pump beam 75 is reflected off mirror 81 onto emitter crystal 83. The emitter crystal is angled with respect to the magnet and the incident beam 75 so that the emitted THz 85 is parallel to the direction of the

magnetic field. The THz 85 is transmitted through THz window 87 which is located in the upper surface 78 of emitter space 73.

Figure 10 shows a variation on the emitter of Figure 9. The same reference numerals are used to denote the same features in both Figures 9 and 10. Therefore, these features will not be repeated here. The compact emitter here is capable of being cooled to very low temperatures. To achieve this cooling, the crystal 83 is mounted on a Peltier cooling element 89. The emitter space 73 has a vacuum port 91 such that the air within the emitter space can be evacuated.

Figure 11 shows a further variation on the compact emitter structure of Figures 9 and 10. Again, the description of like features will not be repeated. The detection crystal 83 is mounted on an electro magnet or a permanent magnet 93. The electro magnet or permanent magnet causes a magnetic field which is normal to the surface of the emitter crystal 83. The THz beam 85 is again produced by refraction of the pump beam 75 of the surface of the semiconductor emitter crystal 83. The angle of incidence of the pump beam 75 is chosen so that there will be a component of the magnetic field in the direction of the THz beam output 85.

The geometry in these and other figures is also chosen such that the angle of incidence of the pump beam θ_B is Brewster's angle for the crystal in question.

Figure 12 shows a further variation on the compact emitter structure. As for Figure 9, an electro magnet or permanent magnet 71 is formed with an aperture 73 which provides a sample space. The aperture is bounded at a lower surface 72 and an upper surface 74 by material which is not part of the magnet 71. A THz window 87 is formed in the upper surface of the bounding material 74. A hole 95 is formed in a side wall of the magnet 73. This hole forms a channel for the visible pump beam 75. The hole is positioned such that the visible pump beam can be shone through the hole directly onto emitter crystal 83 without the need of mirrors within the compact emitter itself. The

reflected THz beam 85 is transmitted from the compact emitter through THz window 87.

Figure 13 shows a further variation on the emitter of Figure 12. Here, as described with reference to Figure 10, the crystal 83 is mounted on Peltier cooling element 89. The emitter space defined by aperture 73 must be evacuated. Therefore a vacuum port 91 is provided on a lower surface 77 of the compact emitter. The visible pump beam is again introduced into the compact emitter along channel 95. The pump beam entering the emitter is sealed with a window or lens 97.

Figure 14 shows a THz emitter in accordance with a further embodiment of the present invention. The relationship between the input beam and the output beam with respective surface normal of the same as described with references to Figure 1. Therefore, these features will not be repeated. However, the THz emitter crystal is different in Figure 14 to that of Figure 1. In Figure 14, the THz emitter crystal (101) is imbedded with magnetic ions Mn^{2+}. The strong S-D exchange interaction between the electron spins and the imbedded Mn^{2+} ions is known to amplify the frequency of the electron spin precession under the applied magnetic field. This results in field tuneable oscillations in the magnetic component of spin. It is known that these oscillations occur at THz frequencies. The frequencies given by the spin split energy $g\mu_B$ where B is the applied magnetic field and μ_B is the Bohr magneton. The increase in energy owing to the presence of interactions between carriers and the magnetic ions is given by the enhanced value of the g factor, which ranges from 2 in non-magnetic samples all the way to 430 or larger in magnetic samples. It is believed that enhanced g-factors may result in accelerations associated with electron spin of the radiated $g\mu_B$ in the THz range. In Figure 14, the magnetic field is arranged perpendicular to the surface normal and photo injected carrier spins.

Another mechanism for enhanced Terahertz emission from magnetically doped semiconductors is the enhanced internal magnetic field associated with the ions, which leads to further acceleration of charge in the semiconductor and hence higher Terahertz

emission powers. With the application of a small external magnetic field (e.g. several hundred millitesla, readily achieved with permanent magnets), the moments of the Mn2+ ions are aligned.

One motivation for introducing magnetic ions into the semiconductor is to reduce the magnetic fields required for THz enhancement from the several Tesla values suggested above, which may require superconducting magnets, to $B<2T$ achievable with permanent or electromagnets. Moreover, even is semiconductors where significant enhancement of the visible to THz conversion efficiency occurs at low magnetic fields, the addition of magnetic ions will further enhance the field, and hence conversion efficiency, achievable. To see this, note the net field inside a magnetically-doped semiconductor is given by

$$B_{net} = B_{applied} + \mu_o M_x^{Mn}$$

where $B_{applied}$ is the externally applied field inside the semiconductor (denoted simply by B in the preceding discussion). μ_o is the permeability and M_x^{Mn} is magnetization associated with the ions; thus $B_{ion} = \mu_o M_x^{Mn}$ is the magnetic field in the semiconductor in the presence of the magnetic ions.

The ultrafast laser sources can be those described. The laser must operate at frequencies at or above the band gap of the material in order to create photocarriers. Circular polarisation of the pump beam is generally required, achieved using standard quarter wave plates, if the spin of the photocarriers is to be oriented parallel to the surface normal.

The magnetically doped may be fabricated in a number of ways:

Numerous types of magnetically doped frequency conversion members 101 are possible. Bulk $Zn_{1-x=0.9}Mn_{x=0.1}Se$ grown on <100> GaAs or other compatible substrates are one

class of structure. X=0 to 0.1 have been studied using optical and ESR characterisation techniques, but higher concentrations x are possible using MBE.

(Ga,Mn)As bulk layers are other systems for realising internal magnetic fields to supplement the externally applied field. (Ga,Mn)As can be grown on (001) GaAs substrates using techniques such as low temperature MBE. For example, 100nm GaAs buffer layers may be grown at 570 C, followed by $0.2\mu m$ $(Al_xGa_{1-x})As_{0.8}$ etch stop layer for any processing and mesa isolation. This layer is grown at 670 C. Finally, a $2\mu m$ (Ga,Mn)As layer is grown. Typical Mn concentrations are in the range 0.043, although other concentrations are possible using MBE.

ZnCdSe/ZnSe quantum wells on <100> GaAS having different concentrations of Mn2+ form an important class of structures. Discrete fractional monolayer planes of the binary magnetic semiconductor MnSe are incorporated into the ZnCdSe wells. The quantum well region thus consists of monolayers of the randomly diluted quartenary alloy (ZnCd,Mn)Se separated by nonmagentic layers of say $Zn_{0.8}Cd_{0.20}Se$. The introduction of magnetic ions into the crystal lattice greatly enhances the effective g factors of the electron and hole bands through strong spin sensitive J_{sp-d} exchange interaction between the s-like (p-like) conduction (valence) band and the local 3d electrons that comprise the spin-5/2 paramagentic Mn2+ moment. There are advantages to various distributions of the magentic ion layers in the quantum wells. For example, for a fixed number of Mn spins, the g-factor may be enhanced by spreading the distribution of MnSe from a single, thick layer placed at one position in the ZnCdSe well, to several layers distributed in different planes throughout the well. This also mitigated against dephasing phenomena due to ion-ion interactions.

Figure 15 shows an experimental arrangement for measuring THz output from a magnetically doped semi-conductor. As many of the features are the same as described in reference to Figure 2, these will not be repeated. The main variation on the equipment of Figure 2 is the variation in the orientation between the magnetic field and the emitted THz. Here, the pump beam is transmitted onto a magnetically doped semi-

conductor crystal emitter in the direction parallel to the surface normal of the semi-conductor crystal emitter. The magnetic field B is arranged so that it is parallel to the surface of the semi-conductor crystal emitter. The THz beam (57) is emitted parallel to the surface normal of the emitter. The beam (47) is then reflected off beam-splitter (121) which reflects the THz-beam onto mirror (123) and into the electro-optic sampling unit (59). The beam-splitter (121) allows transmission of the pump beam onto the cryostat window. The beam splitter may be a suitable material such as cellulose nitrate, mylar, or other materials that are ideally non-lossy and non-dispersive at both THz and visible/near-infrared frequencies.

Figure 16 shows a further embodiment of the present invention. Here, an external bias is applied via contacts 201) and 203 across the surface of the THz emission crystal 205. The THz emission crystal 205 can be any of the type previously described. It may also be a magnetically doped structure.

The incident pump beam 207 then impinges on the emitter 2 or 5 in the region between the two contacts 201 and 203. The bias between the two contacts causes a lateral photo-current to arise. The magnetic field 209 is incident on the sample at an angle of θ (theta) so that the emitted THz experiences a component of the magnetic field. The THz may be emitted via refraction or transmission through the sample 205.

Contacts 201 and 203 may take many forms. For example, as shown is Figure 16a, the contacts may be regular, rectangular contacts. However, as shown in Figure 16b, the contacts may be made in the shape of a bow tie antenna.

The contacts 201 and 203 may be Ohmic contacts. The distance between the two contacts may be varied between several microns to several millimetres.

Figure 17 shows a further arrangement used to enhance the field at the surface to enhance THz emission. Figure 17a shows and experimental arrangement similar to that of Figure 1. However, here, the emitter crystal has a front gate 301 located on the

surface on which the pump beam impinges. The front gate 301 is a Schottky gate, the gate acts to modify the shape of the surface field in the semiconductor to enhance the THz emission. The gradient to the surface field enhances carrier acceleration at the surface and this enhances THz emission.

Typically, the gate will be fabricated from Au, NiCr etc.

CLAIMS:

1.   A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to irradiation with an input beam with a frequency different to that of the emitted radiation, the source being subjected to a magnetic field which has a component parallel to that of the emitted beam of radiation, the emitted beam of radiation being produced by reflecting the input beam off a surface of the frequency conversion member.

2.   A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the frequency conversion member comprises a magnetic material dopant.

3.   A radiation source according to claim 2, wherein the dopant is Mn.

4.   A radiation source according to either of claims 2 or 3, wherein the input beam is circularly polarised.

5.   A radiation source comprising a frequency conversion member configured to emit a beam of emitted radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the emitted beam, the source being subjected to a magnetic field, the source further comprising means for applying an electric field at the surface of the frequency conversion member which is irradiated by the input beam.

6.   A radiation source according to claim 5, wherein the means for applying an electric field comprise a pair of Ohmic contacts provided to the frequency conversion member and means for applying a potential difference across said Ohmic contacts.

7. A radiation source according to claim 6, wherein the Ohmic contacts have a substantially triangular shape such that the contacts taper towards one another.

8. A radiation source according to claim 5, wherein the means for applying a field comprises a Schottky gate provided on the surface of the frequency conversion member which is irradiated by the input beam.

9. A radiation source according to any of claims 2 to 8, wherein the magnetic field has a component parallel to that of the emitted beam.

10. A radiation source according to any of claims 2 to 9, wherein the emitted beam is produced by reflection of the input beam off a surface of the frequency conversion member.

11. A radiation source according to any preceding claim, wherein the magnetic field is oriented parallel to the emitted beam.

12. A radiation source according to any preceding claim, wherein the magnetic field is oriented at an angle of at most 20° to the emitted beam.

13. A radiation source according to any preceding claim, wherein the frequency conversion member is selected from InAs, InSb and GaAs.

14. A radiation source according to any preceding claim, configured such that the angle between the input beam and the surface normal of the frequency conversion member is substantially the Brewster angle

15. A radiation source according to any preceding claim, wherein the frequency conversion member is subjected to a magnetic field of at least 2T.

16. A radiation source comprising a frequency conversion member configured to reflect a beam of reflected radiation with at least one frequency in the range from 0.1 THz to 100 THz, in response to be irradiated with an input beam with a frequency different to that of the reflected beam and a magnet for subjecting the conversion member to a magnetic field which has a component parallel to that of the reflected beam.

17. A radiation source as hereinbefore described with reference to any of the accompanying drawings.

A Radiation Source

ABSTRACT:

A radiation source comprising a frequency conversion member (1) configured to emit a beam of emitted radiation (7) with at least one frequency in the range from 0.1 THz to 100 THz, in response to irradiation with an input beam (3) with a frequency different to that of the emitted radiation (7), the source being subjected to a magnetic field (9) which has a component parallel to that of the emitted beam of radiation (7), the emitted beam of radiation being produced by reflecting the input beam off a surface of the frequency conversion member (1). The radiation source may also comprise a magnetically doped frequency conversion member or also have means for applying an electric field.

(Fig. 1).

1116

P_{THzTM}

P_{THzTE}

Magnetic field parallel to THz beam.

Reflected THz beam

k_{THz}

Surface normal

θ_r

θ_i

Semiconductor THz emitter (InAs, InSb, etc)

Transmitted THz beam

k_{pump}

P_{visTE}

Visible/near-IR generation beam =pump beam
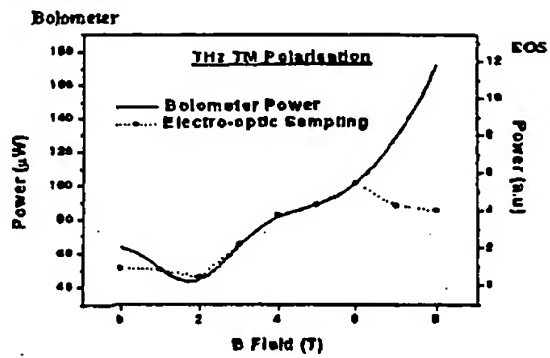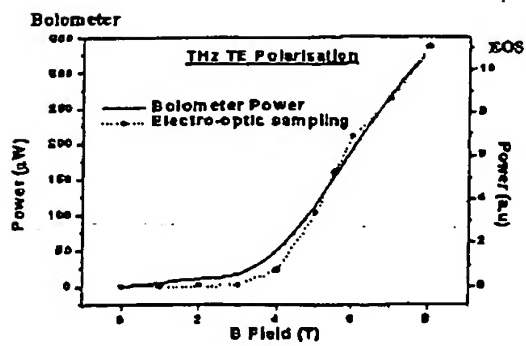
P_{visTM}
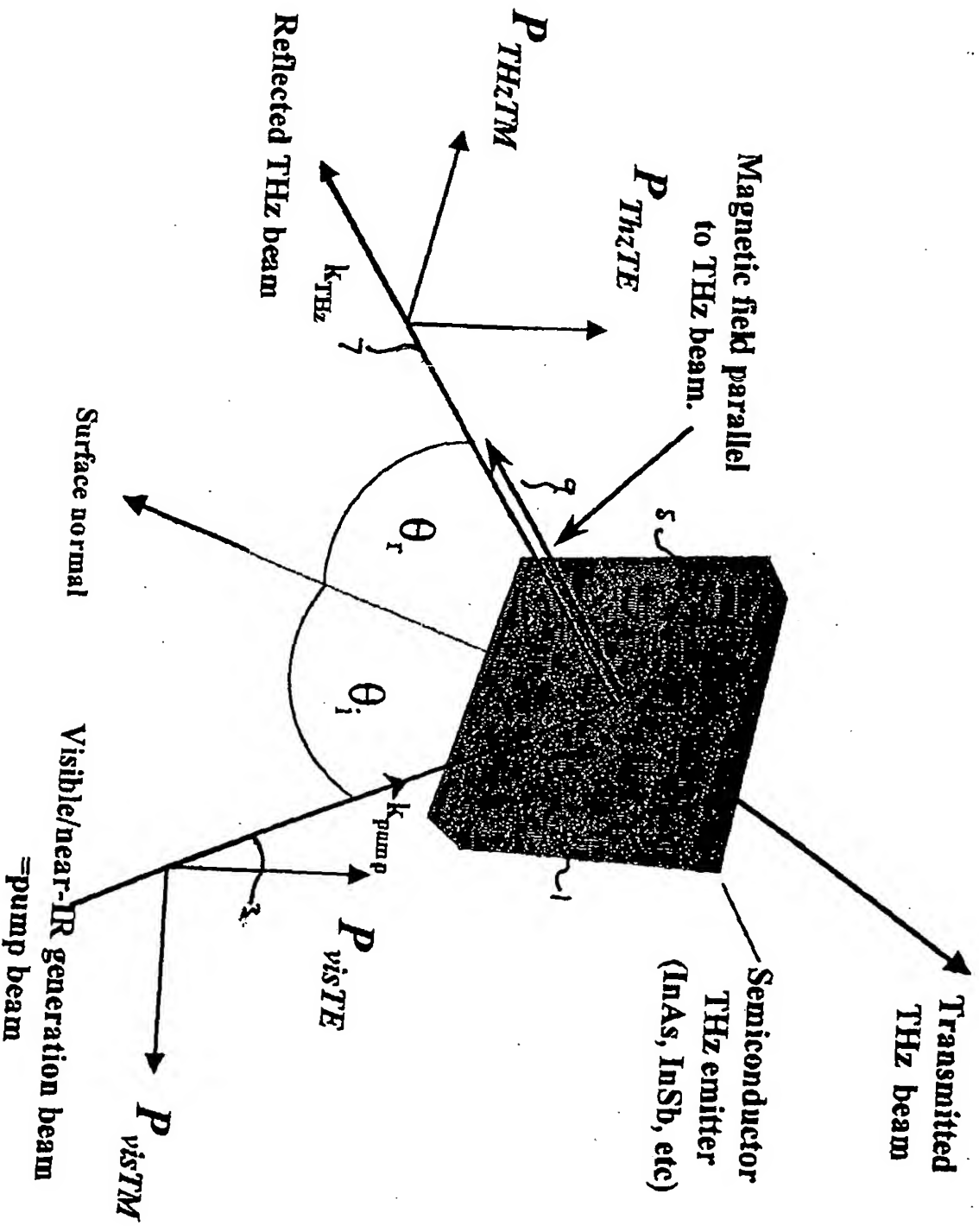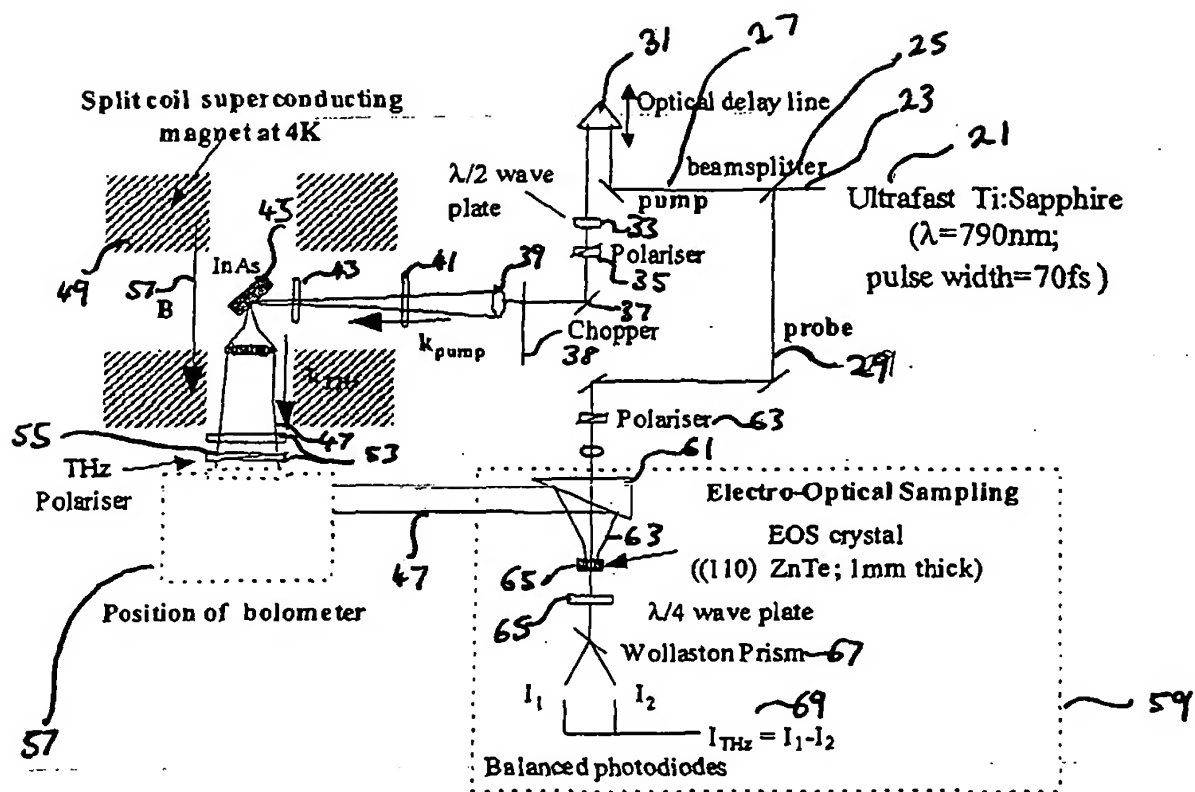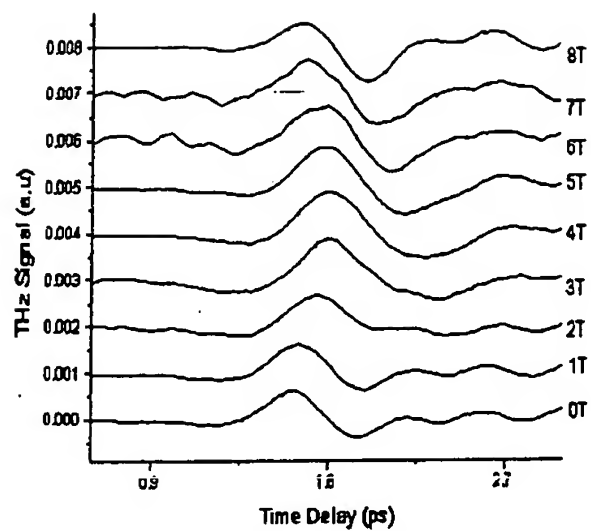
FIGURE 1
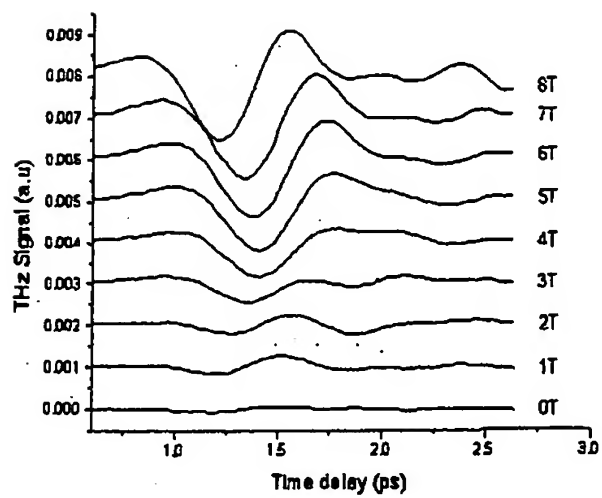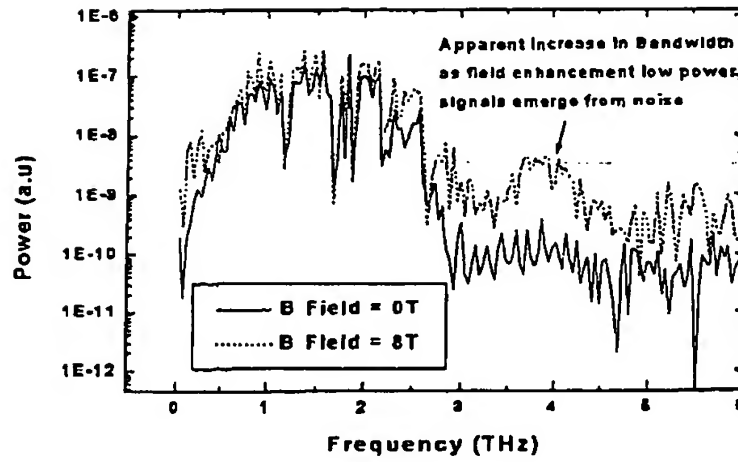
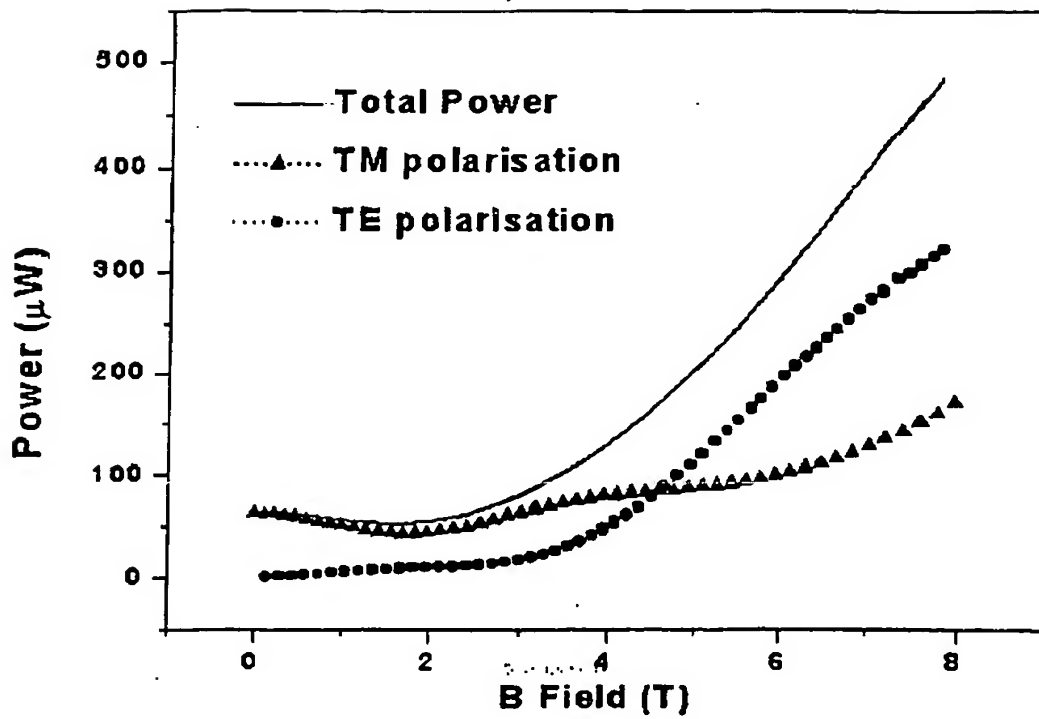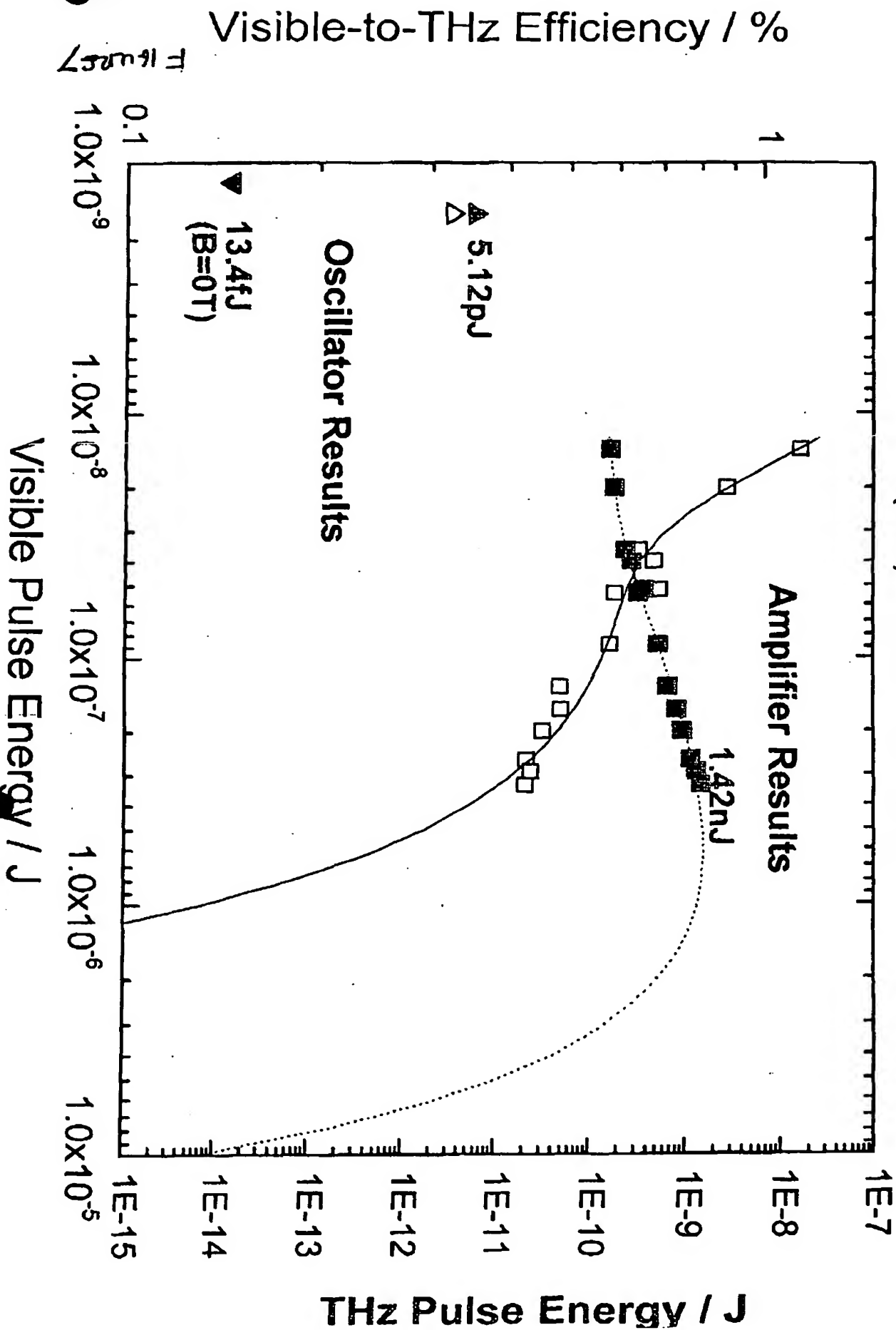FIGURE 2
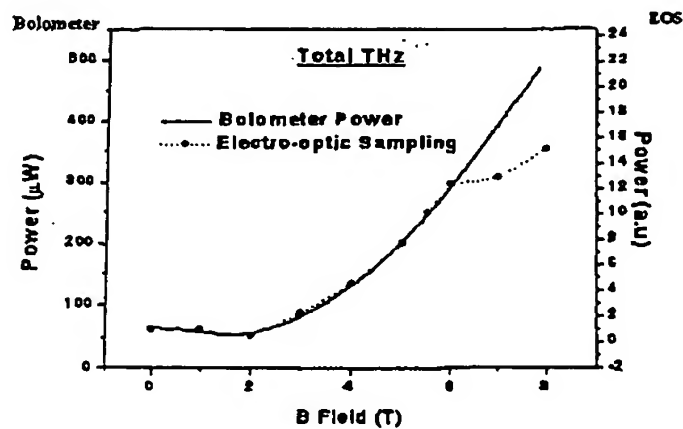
FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

Conversion Efficiency and THz Pulse Powers for (100) InAs at 180K and B=8T

(A)
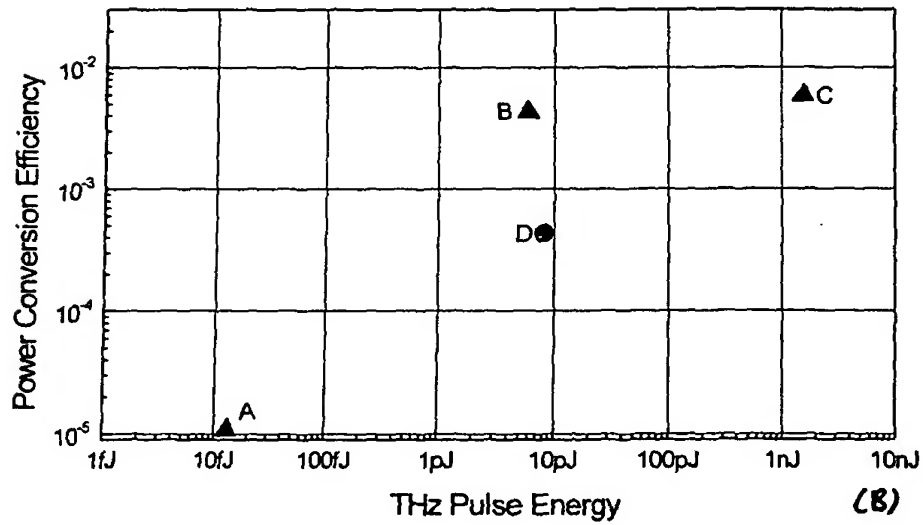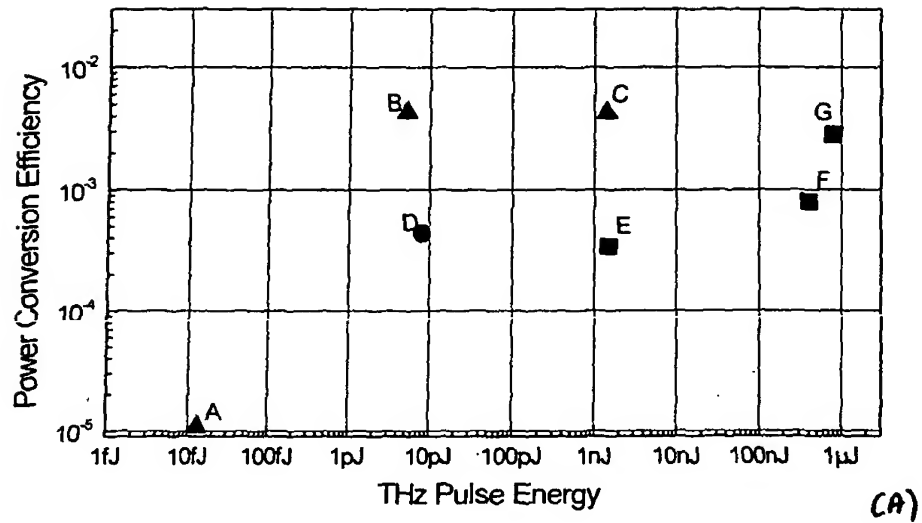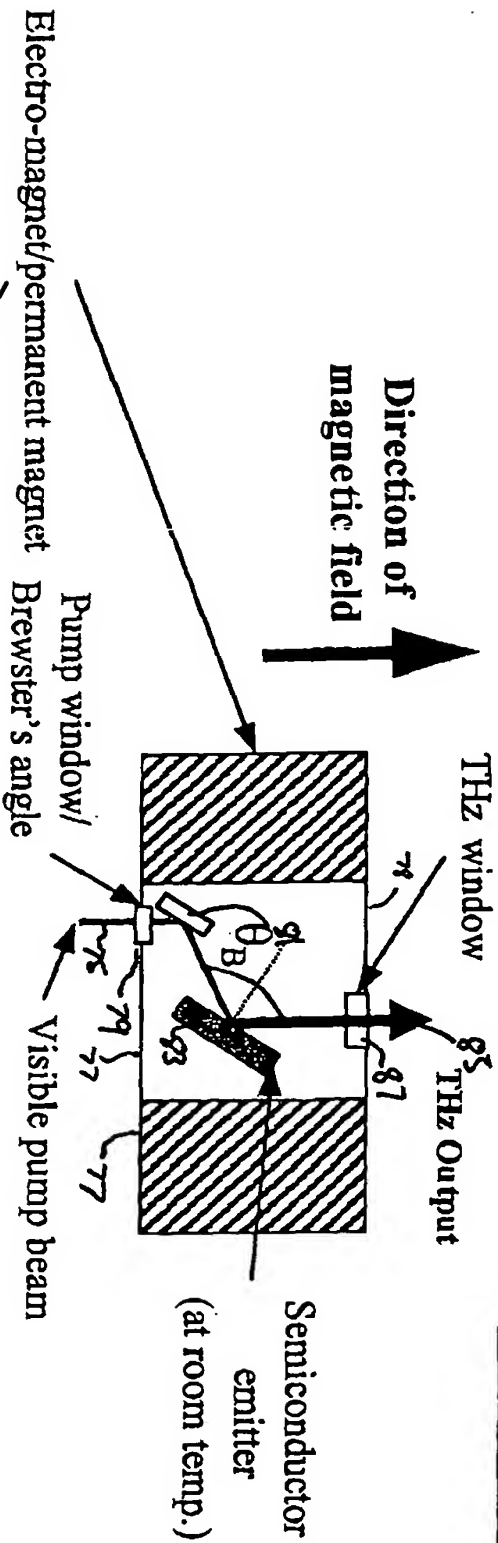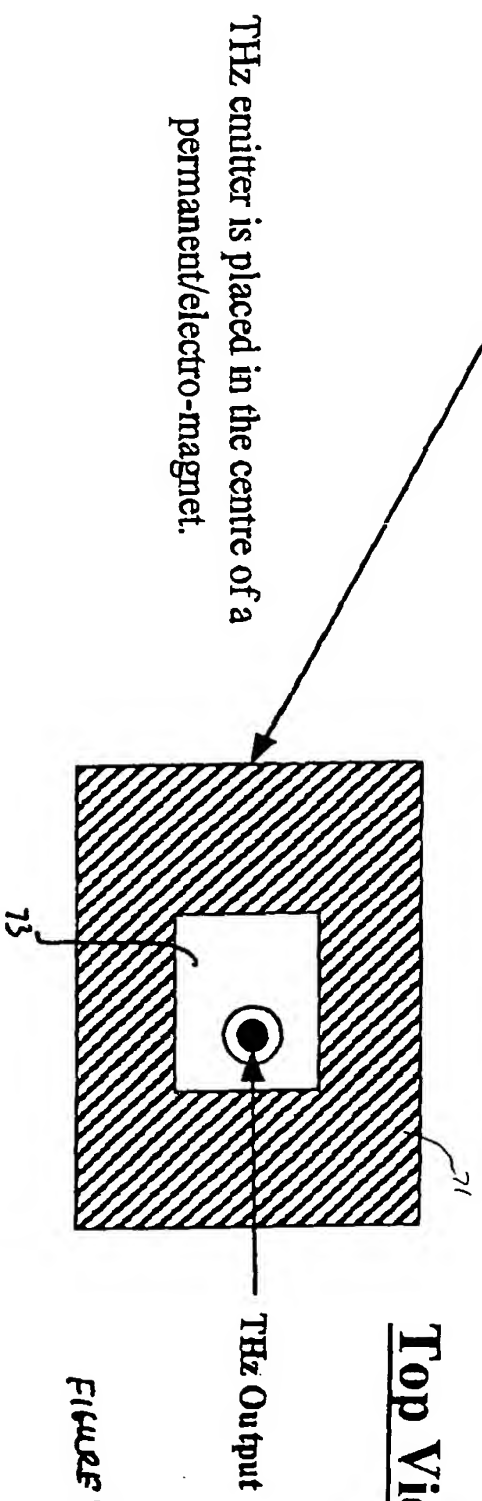

(B)

FIGURE 8

Side View

Direction of
magnetic field

THz window

Pump window/
Brewster's angle

θ_B

Visible pump beam

Semiconductor
emitter
(at room temp.)

THz Output

Electro-magnet/permanent magnet

Top View

THz emitter is placed in the centre of a
permanent/electro-magnet.

THz Output

Figure 9

FIGURE 10

Figure 11

Semiconductor
emitter
(at room temp.)

THz Output
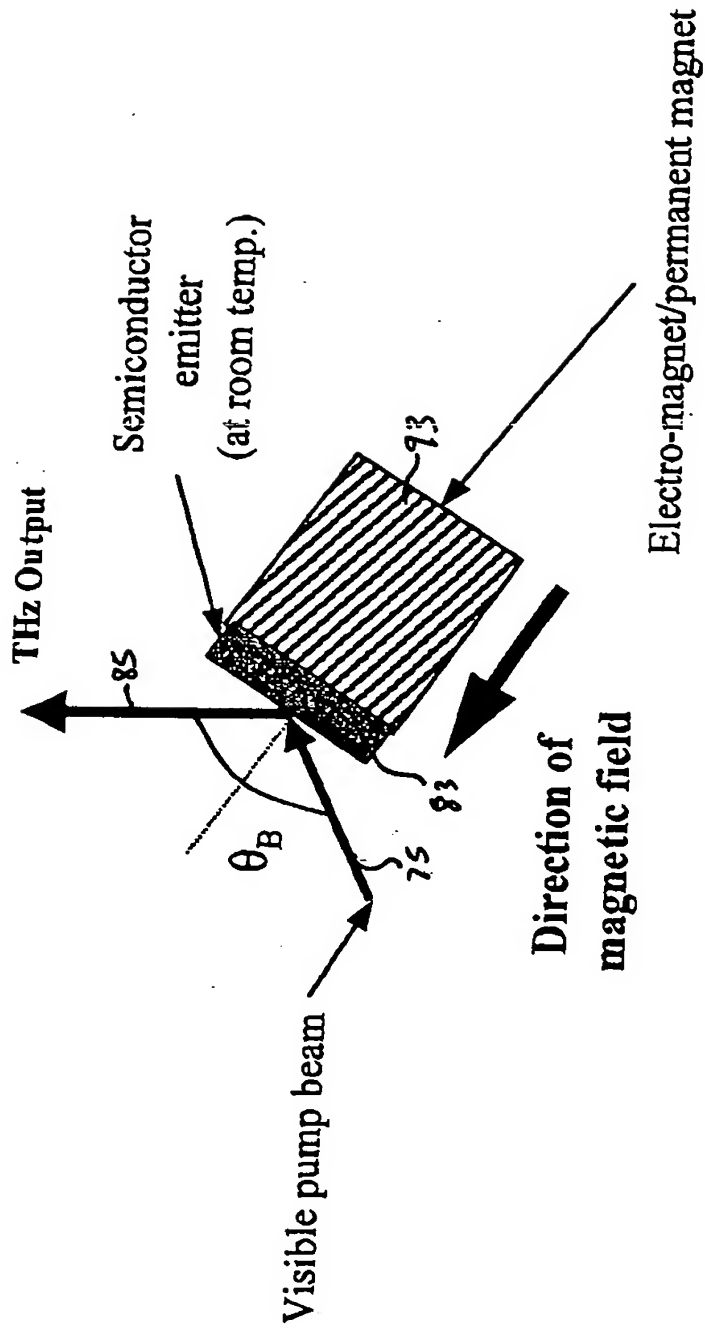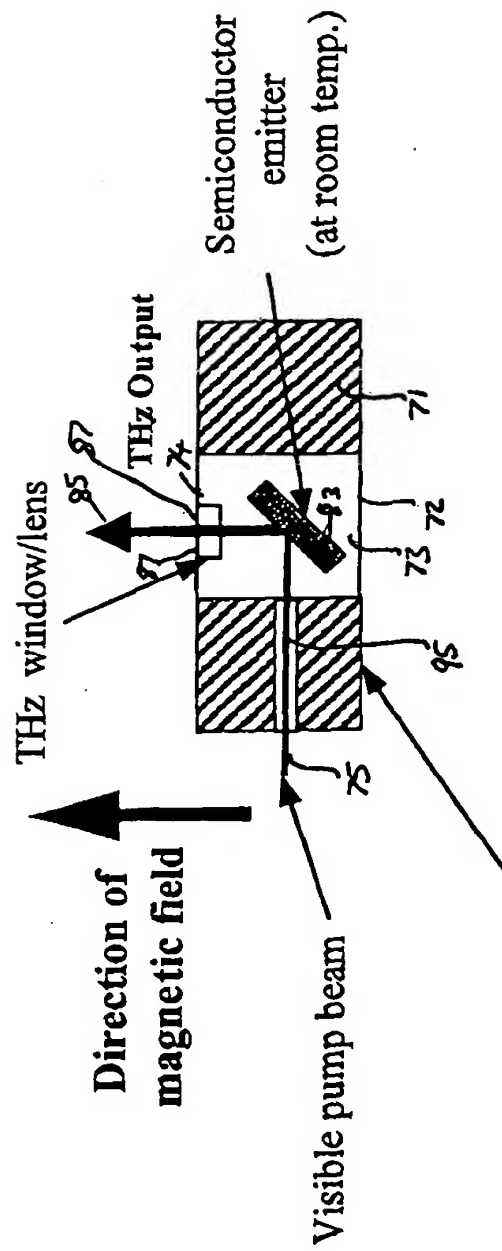
THz window/lens

Direction of
magnetic field

Visible pump beam
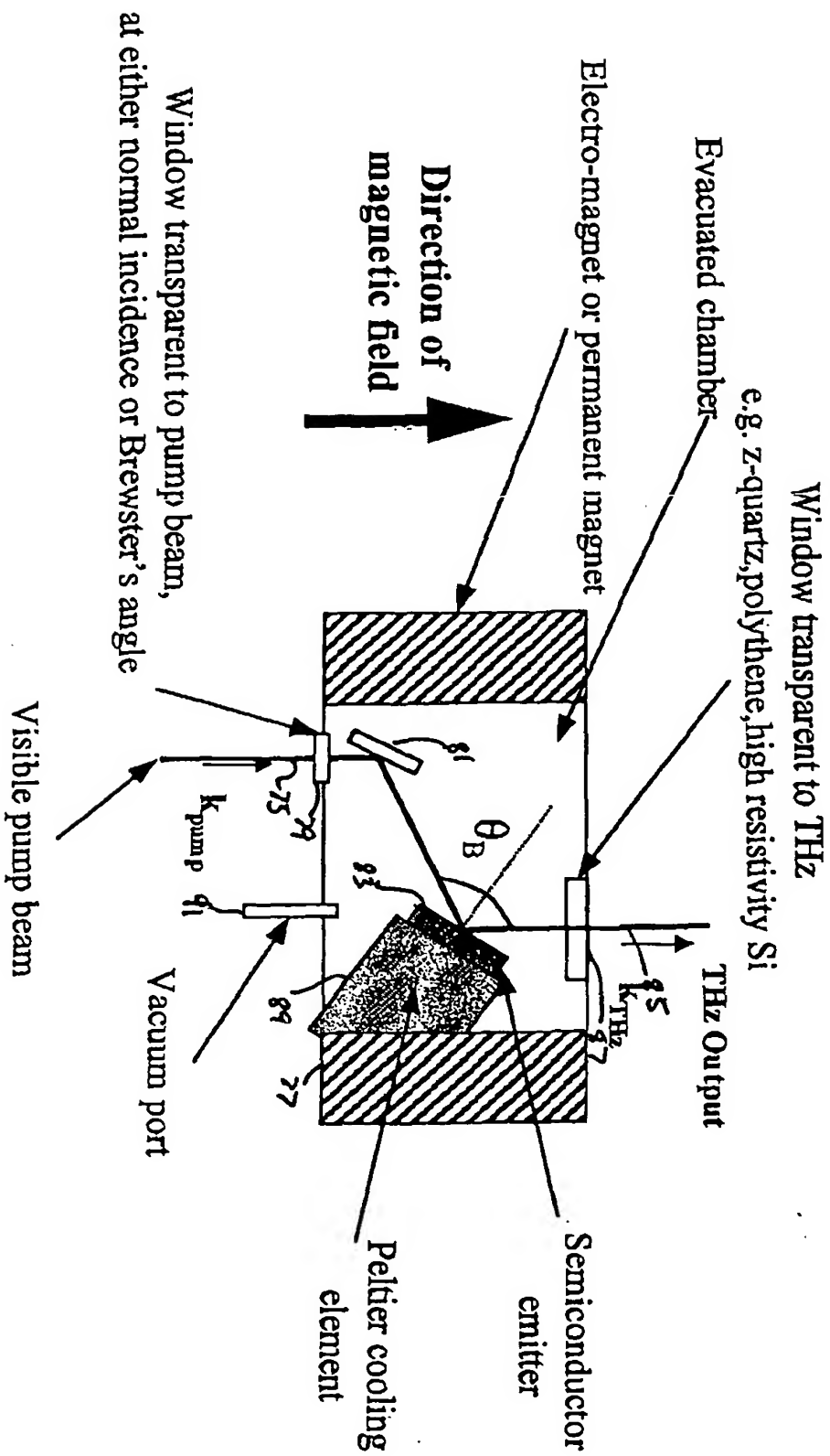
Electro-magnet/permanent magnet

THz emitter is placed in the centre of a
permanent/electro-magnet.

FIGURE 12

Semiconductor
emitter
(at room temp.)

Peltier cooling
element

THz Output

THz window/lens

Vacuum port

Direction of
magnetic field

Visible pump beam

Pump beam window/lens

Electro-magnet/permanent magnet
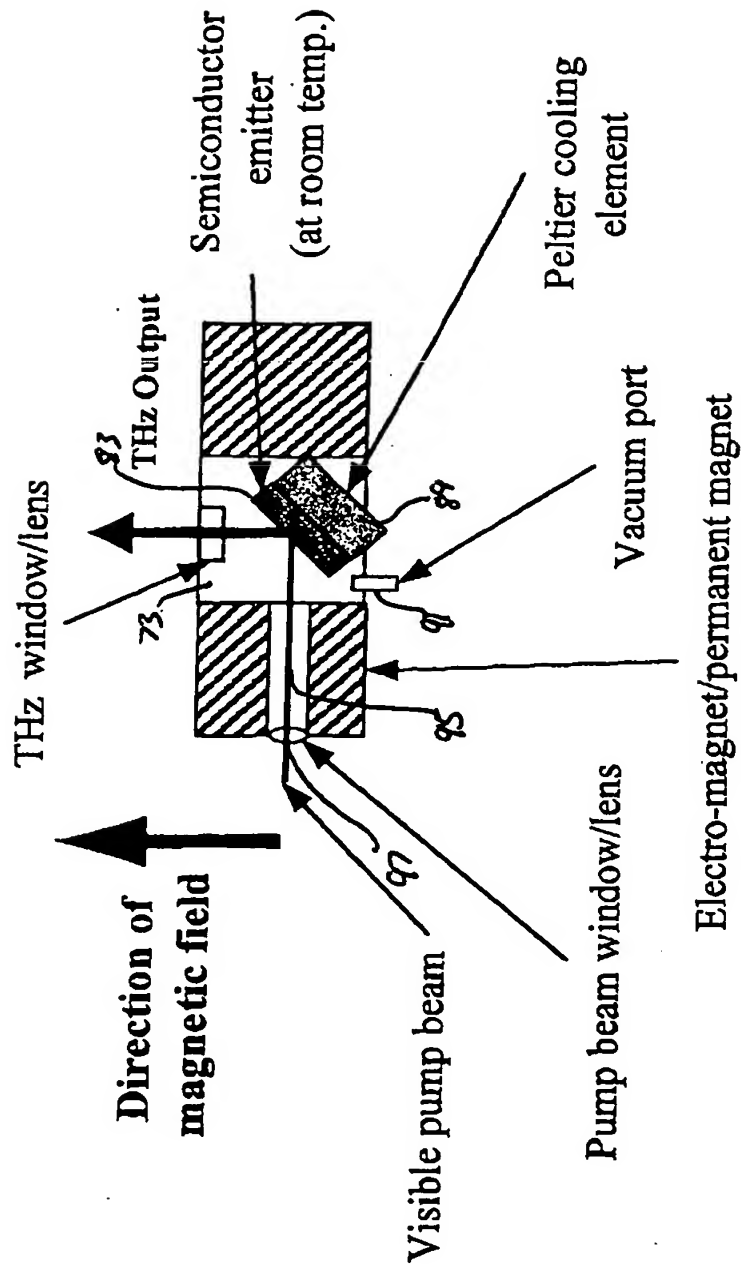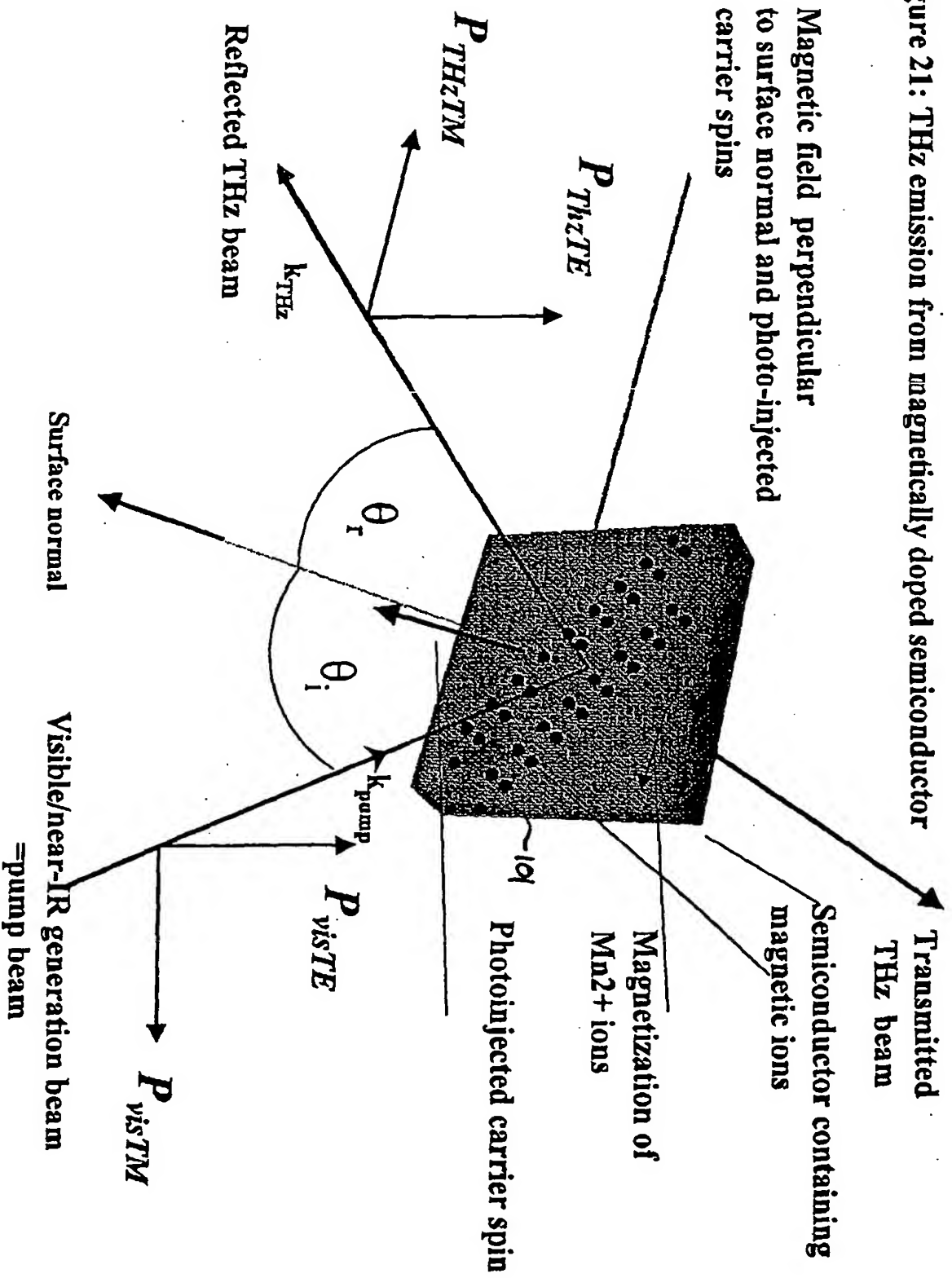
FIGURE 13

Figure 21: THz emission from magnetically doped semiconductor

P_{THzTM}

Reflected THz beam

k_{THz}

P_{THzTE}

Magnetic field perpendicular to surface normal and photo-injected carrier spins

θ_r

θ_i

Surface normal

Transmitted THz beam

Semiconductor containing magnetic ions

Magnetization of Mn2+ ions

Photoinjected carrier spin

$\mid q$

k_{pump}

P_{visTE}

Visible/near-IR generation beam =pump beam

P_{visTM}

FIGURE 14

14116

FIGURE 15

Side view

k_{pump}

θ

207

Magnetic field direction

209

fs laser pulse

E-field

External Bias

203

205 201

Emitted THz Field

External Bias

Top view (a)

β

d

201 203 205

External Bias

Top view (b)

d

201 200 205

$\bigotimes$ k_{pump}

FIGURE 16

Transmitted
THz beam

β_B

Front Schottky
gate

Magnetic field

P_{ThzTE}

301

P_{THzTM}

θ_B

V_{bias}

ϕ_r

ϕ_i

k_{pump}

k_{THz}

(a)

Reflected THz beam

Surface normal

P_{visTE}

P_{visTM}

Visible/near-IR generation beam
=pump beam

Schottky Gate

Semiconductor

V_{bias} increases the
surface field gradient
(dashed lines)
=> Increases carrier
acceleration.

Emitted THz
Field

Magnetic field

(hv)

Pump beam

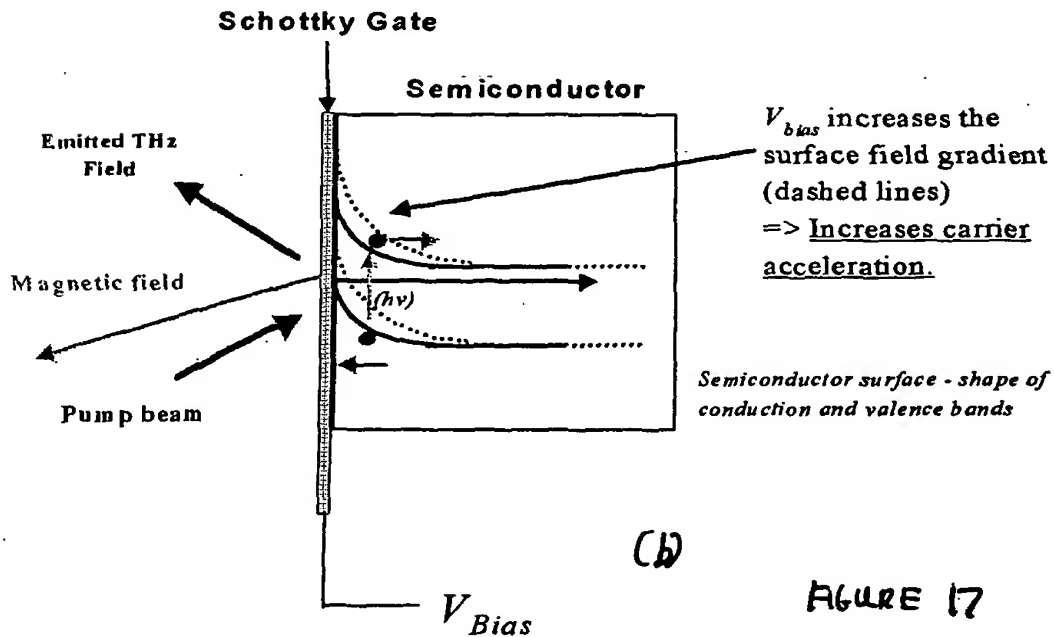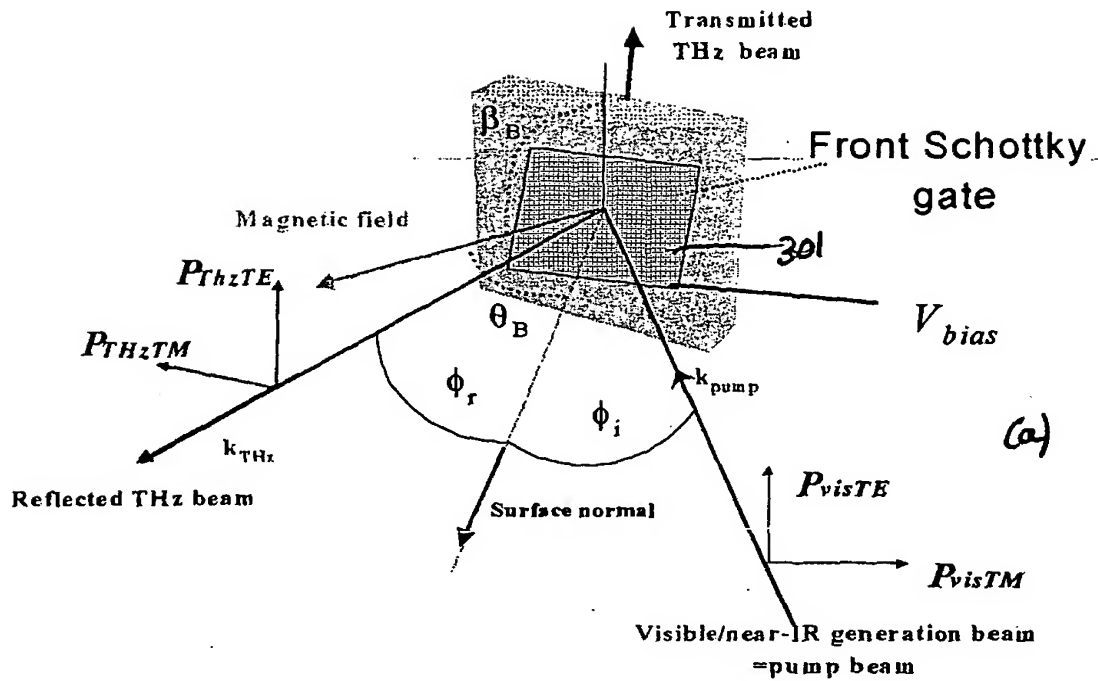Semiconductor surface - shape of
conduction and valence bands

(b)

V_{Bias}

FIGURE 17

PCT/GB00/0309

Sarah Griffin